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A NUMERICAL STUDY OF THE THERMAL STABILITY OF LOW-LYING CORONAL LOOPS

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INTRODUCTION

It has recently been shown that for low-lying loops with a maximum height of $\lesssim$ 5000 km there exists a "cool" solution to the static energy and force balance equations (Antiochos and Noci, 1986; Hood and Priest, 1979). In contrast to the well-known hot solution, with temperatures in the range of 10^6 K, the cool solution reaches a maximum temperature of only a few tens of thousands of degrees. Either of these solutions is possible for a given amount of energy deposited in the loop.

The existence of cool solutions has important implications for the interpretation of UV and X-ray observations, not only of the sun, but of all late-type stars that exhibit transition regions and coronae. The apparently universal rise in emission measure for decreasing temperature below 10^5 K might be explained by an unresolved mixture of both hot and cool loops, for example. In addition, certain kinds of solar features, such as fibrils and active region filaments, may be accurately described as cool loops. Other possible applications abound.

An important property of all static loops is their thermal stability. Even if a solution to the governing equations exists, it may not be physically realizable if it is unstable to small amplitude perturbations. Antiochos *et al.* (1985), among others, have performed detailed linear analyses of the stability of coronal loops. They find that for low-lying loops which admit both a hot and a cool solution, the hot solution is thermally unstable while the cool solution is thermally stable. This suggests that low-lying hot loops do not occur in abundance. Higher arching hot loops appear to be thermally stable, on the other hand, so their ubiquitous appearance on the sun is easy to understand.

One implication of the linear results is that the solar atmosphere should have a two component structure. For a dipole-like magnetic configuration, one envisions a set of small, cool loops nested inside an arcade of larger, hot loops, as indicated in Figure 1. The boundary between these two regions may be quite sharp, in which case there is a thin, secondary transition region several thousand kilometers above the photosphere. Another implication is that the compact X-ray bright points (bipolar regions) discussed elsewhere in these proceedings should be short lived, even for steady energy input.

Any linear stability analysis is, of course, only valid in the limit of small amplitude disturbances. It does not determine what happens to these disturbances when they grow into the non-linear, physically observable regime. If they continue to grow, then the system is truly unstable; however, if the

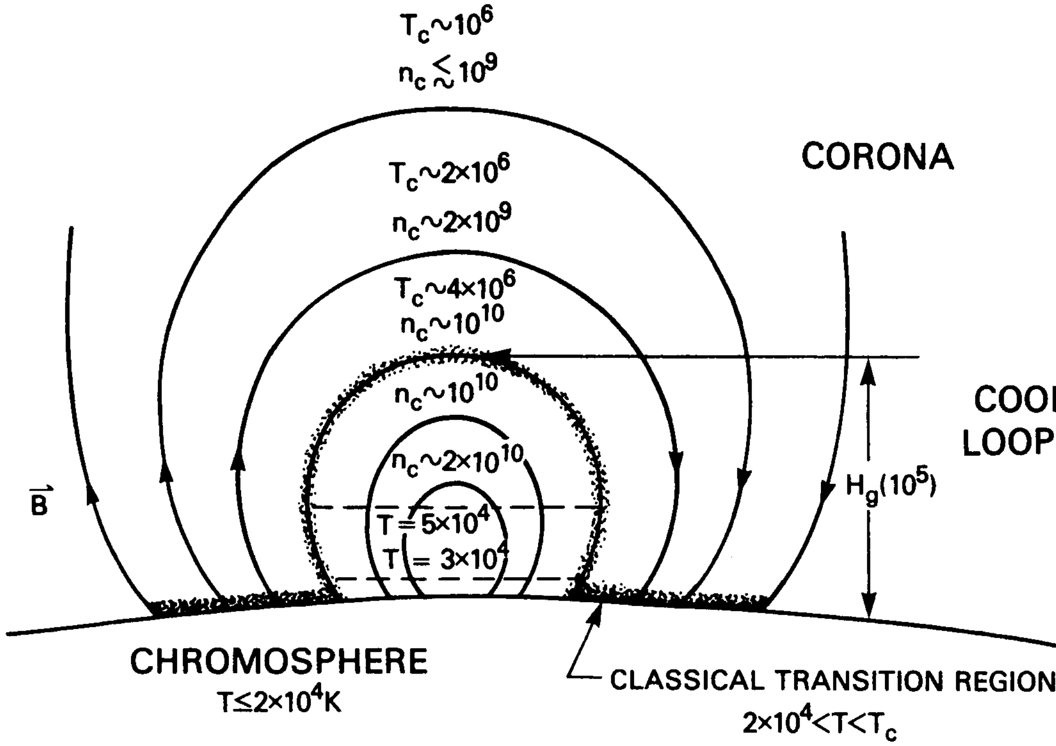

Figure 1. A hypothetical magnetic arcade consisting of cool inner loops surrounded by hot outer loops. Coronal temperatures and densities are given for a heating rate that is proportional to the square of the magnetic field strength. Notice that the cool loops have a maximum height on the order of the gravitational scale height at 10^5 K, or roughly 5000 km.

disturbances quickly saturate, then the system is for all practical purposes stable. We have therefore set out to study the non-linear evolution of loops that are subjected to a variety of small but finite perturbations. Only low-lying loops are considered, since the linear analysis suggests that higher loops are stable.

THE MODEL

We perform our analysis numerically using a one-dimensional hydrodynamic model developed at the Naval Research Laboratory. As described by Mariska et al. (1982), the computer code solves the time-dependent equations for mass, momentum, and energy transport. The radiation law of Raymond modified by a T^3 dependence below 10^5 K is employed, and uniform volumetric heating is assumed. The bottom of the loop atmosphere contains two scale-heights of chromosphere at 10^4 K, so the rigid wall boundary conditions should not be critical.

Our primary interest at this point is in active region filaments, hence we consider a geometry appropriate to those structures. The loop is a total of 6×10^4 km long and is quite flat. Its maximum height is approximately 10^3 km

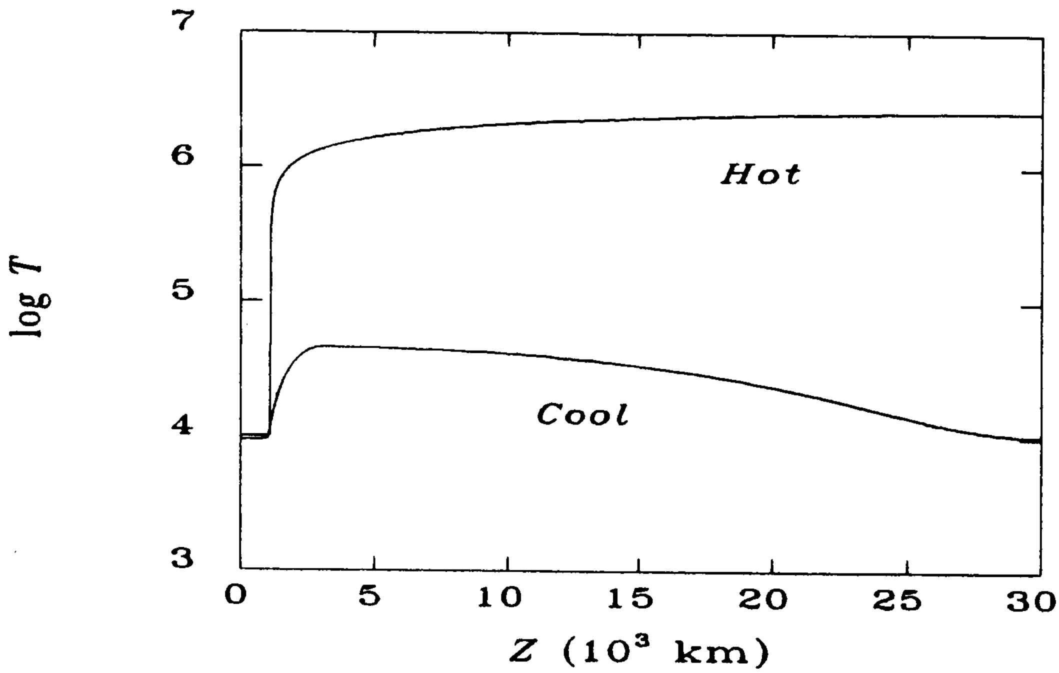

Figure 2. The temperature structure of the hot and cool solutions to the initial static loop. Only half of the symmetric loop is shown. The temperature differences at the end of each perturbation simulation are imperceptible on the scale of this plot.

above the chromosphere, so linear theory predicts it to be unstable. The loop has a very gradual dip in the center to form a gravitational well where dense prominence material could collect. Although a linear stability analysis has not been performed on loops with such a geometry, we expect that, if anything, the central dip will have a destabilizing influence.

The upper curve in Figure 2 shows the temperature profile of the hot solution in this geometry. Only half the loop is shown, as we assume at the outset that it is symmetric. The peak temperature is 2.6×10^6 K and occurs at the loop midpoint. The pressure at the top of the chromosphere is 2.6 dynes cm^{-2}.

The lower curve in the figure is the corresponding cool solution profile for the same energy input. It peaks near the loop apex (where the dip begins) at a value of only 4.7×10^4 K. The pressure of this solution is 0.2 dynes cm^{-2}, roughly an order of magnitude smaller than in the hot solution.

PERTURBATION SIMULATION

We have subjected both of these static solutions to moderate sized perturbations and allowed them to evolve for several thousand seconds (several cooling times and many sound travel times over the coronal portion of the loop). The first perturbation we considered was a 10 % change in the energy input rate--a decrease of 10 % for the hot solution, and an increase of 10 % for the cool solution. As expected, the temperatures begin to fall and rise, respectively, in response to the heating change. Fairly quickly, however, the

evolution slows and the atmosphere appears to settle into a new equilibrium state. This new state is very similar to the original one for both the hot and the cool cases. At the end of the calculations the temperature has changed by only a few percent at all locations. Therefore, the solutions appear to be stable to small perturbations in the heating.

A second perturbation we considered was an instantaneous sinusoidal velocity disturbance of 2 1/2 wavelengths across the half-loop. So as to remain well below the sound speed, the amplitude was chosen to be 10 km s^{-1} for the hot solution, but only 2 km s^{-1} for the cool solution. As before, the perturbation quickly saturates, and the final state of the loop is essentially identical to the original state. The hot and cool solutions are thus stable to this type of perturbation, as well.

DISCUSSION

These results suggest that both hot and cool loops of the geometry considered here are thermally stable against small amplitude perturbations of all kinds. Presumably low-lying loops of other geometries are also stable, but this remains to be shown. Just what causes the linearly unstable modes identified by Antiochos et al. (1985) to saturate is not clear. We are currently investigating this question.

If correct, our stability conclusion has important ramifications for the nature of low-lying coronal loops. It implies that the current state of a loop is strongly dependent upon the loop history. For example, a hot loop cannot spontaneously evolve into a cool one without some sort of a major event (e.g., a dramatic decrease in the heating rate, or an injection of copious amounts of cool material). In particular, active region filaments cannot spontaneously condense out of the hot corona, as has been suggested in the past. For further discussion of this point, see the contribution of Poland, Mariska, and Klimchuk in these proceedings.

Another implication of stability is that not all low-lying loops must be cool. The picture of Figure 1 may still be correct, but it need not be, as suggested earlier.

And finally, we end with a word of caution. The numerical results presented here must be considered only suggestive. A concern of ours is that the loop we modelled may not have been properly resolved; the grid size of 10 km in the transition region is only marginal. We are currently working on new simulations with a much improved resolution. In addition, we are exploring alternate geometries, such as the more traditional semi-circular loop. These results will be discussed in a future publication.

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